

Black hole lightning due to particle acceleration at subhorizon scales

J. Aleksić,¹ S. Ansoldi,² L. A. Antonelli,³ P. Antoranz,⁴ A. Babic,⁵ P. Bangale,⁶ J. A. Barrio,⁷ J. Becerra González,^{8,25} W. Bednarek,⁹ E. Bernardini,¹⁰ B. Biasuzzi,² A. Biland,¹¹ O. Blanch,¹ S. Bonnefoy,⁷ G. Bonnoli,³ F. Borracci,⁶ T. Bretz,^{12,26} E. Carmona,¹³ A. Carosi,³ P. Colin,⁶ E. Colombo,⁸ J. L. Contreras,⁷ J. Cortina,¹ S. Covino,³ P. Da Vela,⁴ F. Dazzi,⁶ A. De Angelis,² G. De Caneva,¹⁰ B. De Lotto,² E. de Oña Wilhelmi,¹⁴ C. Delgado Mendez,¹³ D. Dominis Prester,⁵ D. Dörner,¹² M. Doro,¹⁵ S. Einecke,¹⁶ D. Eisenacher,¹² D. Elsaesser,¹² M. V. Fonseca,⁷ L. Font,¹⁷ K. Frantzen,¹⁶ C. Fruck,⁶ D. Galindo,¹⁸ R. J. García López,⁸ M. Garczarczyk,¹⁰ D. Garrido Terrats,¹⁷ M. Gaug,¹⁷ N. Godinović,⁵ A. González Muñoz,¹ S. R. Gozzini,¹⁰ D. Hadasch,^{14,27} Y. Hanabata,¹⁹ M. Hayashida,¹⁹ J. Herrera,⁸ D. Hildebrand,¹¹ J. Hose,⁶ D. Hrupec,⁵ W. Idec,⁹ V. Kadenius,²⁰ H. Kellermann,⁶ K. Kodani,¹⁹ Y. Konno,¹⁹ J. Krause,⁶ H. Kubo,¹⁹ J. Kushida,¹⁹ A. La Barbera,³ D. Lelas,⁵ N. Lewandowska,¹² E. Lindfors,^{20,28} S. Lombardi,³ F. Longo,² M. López,⁷ R. López-Coto,¹ A. López-Oramas,¹ E. Lorenz,[†] I. Lozano,⁷ M. Makariev,²¹ K. Mallot,¹⁰ G. Maneva,²¹ N. Mankuzhiyal,^{2,29} K. Mannheim,¹² L. Maraschi,³ B. Marcote,¹⁸ M. Mariotti,¹⁵ M. Martínez,¹ D. Mazin,⁶ U. Menzel,⁶ J. M. Miranda,⁴ R. Mirzoyan,⁶ A. Moralejo,¹ P. Munar-Adrover,¹⁸ D. Nakajima,¹⁹ A. Niedzwiecki,⁹ K. Nilsson,^{20,28} K. Nishijima,¹⁹ K. Noda,⁶ R. Orito,¹⁹ A. Overkemping,¹⁶ S. Paiano,¹⁵ M. Palatiello,² D. Paneque,⁶ R. Paoletti,⁴ J. M. Paredes,¹⁸ X. Paredes-Fortuny,¹⁸ M. Persic,^{2,30} J. Poutanen,²⁰ P. G. Prada Moroni,²² E. Prandini,¹¹ I. Puljak,⁵ R. Reinthal,²⁰ W. Rhode,¹⁶ M. Ribó,¹⁸ J. Rico,¹ J. Rodríguez García,⁶ S. Rügemer,¹² T. Saito,¹⁹ K. Saito,¹⁹ K. Satalecka,⁷ V. Scalzotto,¹⁵ V. Scapin,⁷ C. Schultz,¹⁵ T. Schweizer,⁶ S. N. Shore,²² A. Sillanpää,²⁰ J. Sitarek,¹ I. Snidaric,⁵ D. Sobczynska,⁹ F. Spanier,¹² V. Stamatescu,^{1,31} A. Stamerra,³ T. Steinbring,¹² J. Storz,¹² M. Strzys,⁶ L. Takalo,²⁰ H. Takami,¹⁹ F. Tavecchio,²¹ P. Temnikov,²¹ T. Terzić,⁵ D. Tescaro,⁸ M. Teshima,⁶ J. Thaele,¹⁶ O. Tibolla,¹² D. F. Torres,²³ T. Toyama,⁶ A. Treves,²⁴ M. Uellenbeck,¹⁶ P. Vogler,¹¹ R. Zanin,¹⁸ M. Kadler,¹² R. Schulz,^{12,32} E. Ros,^{33,34,35} U. Bach,³³ F. Krauß,^{12,32} J. Wilms³²

¹IFAE, Campus UAB, E-08193 Bellaterra, Spain. ²Università di Udine, and INFN Trieste, I-33100 Udine, Italy. ³INAF National Institute for Astrophysics, I-00136 Rome, Italy. ⁴Università di Siena, and INFN Pisa, I-53100 Siena, Italy. ⁵Croatian MAGIC Consortium, Rudjer Boskovic Institute, University of Rijeka and University of Split, HR-10000 Zagreb, Croatia. ⁶Max-Planck-Institut für Physik, D-80805 München, Germany. ⁷Universidad Complutense, E-28040 Madrid, Spain. ⁸Inst. de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain. ⁹University of Łódź, PL-90236 Lodz, Poland. ¹⁰Deutsches Elektronen-Synchrotron (DESY), D-15738 Zeuthen, Germany. ¹¹ETH Zurich, CH-8093 Zurich, Switzerland. ¹²Universität Würzburg, D-97074 Würzburg, Germany. ¹³Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, E-28040 Madrid, Spain. ¹⁴Institute of Space Sciences, E-08193 Barcelona, Spain. ¹⁵Università di Padova and INFN, I-35131 Padova, Italy. ¹⁶Technische Universität Dortmund, D-44221 Dortmund, Germany. ¹⁷Unitat de Física de les Radiacions, Departament de Física, and CERES-IEEC, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Spain. ¹⁸Universitat de Barcelona, ICC, IEEC-UB, E-08028 Barcelona, Spain. ¹⁹Japanese MAGIC Consortium, Division of Physics and Astronomy, Kyoto University, Japan. ²⁰Finnish MAGIC Consortium, Tuorla Observatory, University of Turku and Department of Physics, University of Oulu, Finland. ²¹Inst. for Nucl. Research and Nucl. Energy, BG-1784 Sofia, Bulgaria. ²²Università di Pisa, and INFN Pisa, I-56126 Pisa, Italy. ²³ICREA and Institute of Space Sciences, E-08193 Barcelona, Spain. ²⁴Università dell'Insubria and INFN Milano Bicocca, Como, I-22100 Como, Italy. ²⁵Now at NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA and Department of Physics and Department of Astronomy, University of Maryland, College Park, MD 20742, USA. ²⁶Now at Ecole polytechnique fédérale de Lausanne (EPFL), Lausanne, Switzerland. ²⁷Now at Institut für Astro- und Teilchenphysik, Leopold-Franzens- Universität Innsbruck, A-6020 Innsbruck, Austria. ²⁸Now at Finnish Centre for Astronomy with ESO (FINCA), Turku, Finland. ²⁹Now at Astrophysics Science Division, Bhabha Atomic Research Centre, Mumbai 400085, India. ³⁰Also at INAF-Trieste. ³¹Now at School of Chemistry and Physics, University of Adelaide, Adelaide 5005, Australia. ³²Dr. Remeis-Sternwarte Bamberg, Astronomisches Institut der Universität Erlangen-Nürnberg, ECAP, D-96049 Bamberg, Germany. ³³Max-Planck-Institut für Radioastronomie, D-53121 Bonn, Germany. ³⁴Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain. ³⁵Departament d'Astronomia i Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain.

†Deceased.

*Corresponding author. E-mail: deisenacher@astro.uni-wuerzburg.de (D.E.); jsitarek@ifae.es (J.S.); mannheim@astro.uni-wuerzburg.de (K.M.)

Supermassive black holes with masses of millions to billions of solar masses are commonly found in the centers of galaxies. Astronomers seek to image jet formation using radio interferometry but still suffer from insufficient angular resolution. An alternative method to resolve small structures is to measure the time variability of their emission. Here we report on gamma-ray observations of the radio galaxy IC 310 obtained with the MAGIC telescopes, revealing variability with doubling time scales faster than 4.8 min. Causality constrains the size of the emission region to be smaller than 20% of the gravitational radius of its central black hole. We suggest that the emission is associated with pulsar-like particle acceleration by the electric field across a magnetospheric gap at the base of the radio jet.

More than three decades ago it was proposed that the radio emission of extragalactic jets results from a relativistically moving plasma consisting of magnetic fields and accelerated particles following a power-law energy distribution (J). One of the major assets of the model is that it can explain the non-thermal emission of extragalactic jets across the entire electro-

magnetic spectrum, from radio waves up to gamma rays. The emission can be understood as synchrotron radiation and inverse Compton scattering (2, 3) due to particles accelerated at shock waves in the jets. The gamma rays can reach very high energies measured in Giga-electronvolts ($1 \text{ GeV} = 10^9 \text{ eV}$ corresponding roughly to the rest mass energy

equivalent of the proton) and Tera-electronvolts ($1 \text{ TeV} = 10^{12} \text{ eV}$). According to the Blandford-Znajek mechanism, the jets are powered by extracting rotational energy from the black holes which have acquired angular momentum through the accretion of surrounding gas and black hole mergers (4), although so far astrophysical evidence for the role of black hole spin is still lacking (5). For a maximally rotating supermassive black hole of mass $M = 10^8 m_\odot M_\odot$, where $M_\odot$ denotes one solar mass, the size of the jet formation region should be of the order of its gravitational radius $r_g = G_N M / c^2 \sim 1.5 \times 10^{11} m_\odot \text{ m}$ and twice this value for a non-rotating Schwarzschild black hole. Astronomical telescopes do not yet provide the angular resolution needed to image structures on this scale. The highest resolution images of jets obtained with very long baseline radio interferometry show radio-emitting knots traveling down the jets (6). Approaching the black hole, the spectra cut off at increasingly higher frequencies due to synchrotron-self-absorption. Observations at very high frequencies where the core becomes transparent are needed to zoom into the region where the jets are emerging from. The record holder is a very long baseline radio interferometry observation of the jet of the nearby radio galaxy M87 at a frequency of 230 GHz, resolving a source with the size of 11.0 ± 0.8 gravitational radii (7).

The event horizon light-crossing time

While direct imaging of the jet formation region has to await better angular resolution, indirect information about its size can be inferred from the temporal variability of the emission coming from that region. The observed gamma-ray variability time scales indeed reach down to the event horizon light crossing time $\Delta t_{\text{BH}} = r_g / c = G_N M / c^3 = 8.3 m_\odot \text{ minutes}$ (8) vindicating the scenario that the jets originate from the magnetospheres of accreting black holes. An example is the radio galaxy M87 in the Virgo cluster of galaxies (9, 10). This galaxy harbors a central supermassive black hole with the enormous mass of $\sim 6.4 \times 10^9 M_\odot$ (1). M87 exhibits gamma-ray variability at a time scale of days (12) which is consistent with the light-crossing time of the event horizon $\Delta t_{\text{BH}}(\text{M87}) = 0.4 \text{ days}$.

Smaller than a black hole?

Observations of Mrk 501 (13) and PKS 2155 – 304 (14) at very high energies have provided evidence for extreme variability events with flux doubling time scales as short as $\sim 2 \text{ min}$. The ultrafast variability corresponds to $\Delta t < \Delta t_{\text{BH}}$ and therefore casts a shadow of doubt on the current shock-in-jet paradigm. It has been suggested that relativistic bulk motion of the jets could explain the observed time scales (15). The argument relies on the observation that these flaring sources belong to the class of sources that astronomers call blazars. In blazars, the jets are pointing at a small angle toward the observer. Since the jet plasma moves with a speed close to the speed of light $\beta = v/c \simeq 1$ leading to a bulk Lorentz factor $\Gamma_j > 1$, several effects arise due to the relativistic boosting of the emission (16). One of them affects the time scale of flux variations of the emission from a shock. The moving shock plasma almost catches up with its own radiation, and this leads to a shortening of the observed variability time scale Δt compared with the variability time scale $\Delta t'$ in a frame comoving with the shock given by $\Delta t = (1+z)\delta^{-1}\Delta t'$ where z denotes the cosmological redshift of

the source. For a given value of Γ_j , the Doppler factor δ depends strongly on the orientation angle of the jet θ (Fig. 1). Note that $\theta = 0$ corresponds to perfect alignment. For Mrk 501 and PKS 2155 – 304, almost perfectly aligned jets with $\Gamma_j > 50$ would be needed to accommodate for $\Delta t < \Delta t_{\text{BH}}$ and to avoid self-absorption of the gamma rays due to pair production (15). In blazars, interferometric observations of the superluminal motion of radio knots suggest lower values $\Gamma_j \sim 10$ and orientation angles of a few degrees (17). Larger values of Γ_j would lead to a problem with population statistics: the number of unbeamed counterparts of blazars viewed at larger angles would then exceed the number of radio galaxies, commonly believed to represent the misaligned blazars (18). Assuming lower black hole masses would bring down Δt_{BH} . However, lower masses conflict with the firmly established dynamical measurements of black hole masses, and therefore do not seem to be a likely solution of the dilemma. Other possible solutions of this Doppler factor crisis (19) invoke models of structured jets (20, 21) or Poynting flux dominated jets in which only a few but very fast seed particles at the jet base reach high Lorentz factors (22–24), before the Poynting flux is converted into the kinetic energy of the bulk flow by mass entrainment.

All of these attempts to explain the sub-horizon scale variability with relativistic projection effects alone ignore a fundamental problem. If the perturbations giving rise to the blazar variability are injected at the jet base, the time scale of the flux variations in the frame comoving with the jet is affected by time dilation with Lorentz factor Γ_j . In blazars where $\delta \sim \Gamma_j$, the Lorentz factor cancels out, and the observed variability time scale is ultimately bounded below by Δt_{BH} .

IC 310: A gamma-ray lightning inferno

IC 310 is a peculiar radio galaxy located in the outskirts of the Perseus cluster at a distance of 260 million light years from Earth. On November 12/13th in 2012, MAGIC, a system of two Imaging Atmospheric Cherenkov Telescopes located on the Canary island of La Palma (25), detected an extraordinary outburst of gamma rays from this object (see Fig. 2, S1). The details of the analysis can be found in section S2. Prior to these observations, variable gamma-ray emission from IC 310 had already been detected by satellite and ground-based gamma-ray instruments at GeV and TeV energies, e.g., Fermi-LAT and MAGIC (26–28). In the night of the flare in November 2012, the mean flux above 300 GeV was $(6.08 \pm 0.29) \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1}$, i.e., four times higher than the highest flux during previous observations in 2009/2010. The measured spectrum (Fig. 3) can be described by a simple power law with a differential photon spectral index of $\Gamma = 1.90 \pm 0.04_{\text{stat}} \pm 0.15_{\text{sys}}$ in the energy range of 70 GeV - 8.3 TeV (see Table S2). Owing to its proximity, the spectrum of IC 310 is only marginally affected by photon-photon absorption in collisions with the extragalactic background light (EBL).

IC 310 harbors a supermassive black hole with a mass of $M = (3_{-2}^{+4}) \times 10^8 M_\odot$ (see section S1.1) corresponding to an event horizon light-crossing time of $\Delta t_{\text{BH}} = (23_{-15}^{+34}) \text{ min}$. The mass has been inferred from the correlation of black hole masses with the central

velocity dispersion of their surrounding galaxies (29, 30). The reported errors are dominated by the intrinsic scatter of the distribution. The same value of the mass is obtained from the fundamental plane of black hole activity (31). The scatter in the fundamental plane for a single measurement is larger and corresponds to a factor of ~ 7.5 .

During 3.7 hours of observations, extreme variability with multiple individual flares has been detected (Fig. 4, S3, S4). The flare has shown the most rapid flux variations ever observed in extragalactic objects, comparable only to those seen in Mrk 501 and PKS 2155–304. A conservative estimate of the shortest variability time scale in the frame of IC 310 yields $\Delta t / (1+z) = 4.8$ min. It is the largest doubling time scale with which the rapidly rising part of the flare can be fitted with a probability $> 5\%$ (see fig. S4). The light curve also shows pronounced large-amplitude flickering characterized by doubling time scales down to $\Delta t \sim 1$ min. The conservative variability time scale corresponds to 20% of the light travel time across the event horizon, or still 60% of it giving allowance for the scatter in the dynamical black hole mass measurement.

From the absence of a counter radio jet and the requirement that the proper jet length does not exceed the maximum of the distribution of jet lengths in radio galaxies, the orientation angle was found to be in the range $\theta \sim 10^\circ - 20^\circ$ (see section S1.2), and the Doppler factor consistent with $\delta \approx 4$ (32). These values put IC 310 at the borderline between radio galaxies and blazars. The jet power estimated from observations of the large-scale radio jet is $L_j = 2 \times 10^{42} \text{ erg s}^{-1}$ assuming that it contains only electrons, positrons, and magnetic fields in equipartition of their energy densities (see section S1.3). For a radiative efficiency of 10%, the Doppler-boosted average luminosity of the jet emission amounts to $0.1\delta^4 L_j \approx 5 \times 10^{43} \text{ erg s}^{-1}$ which is close to the one observed in very-high energy gamma rays. For $\delta \sim 4$, the variability time scale in the comoving frame of the jet, where it should be larger than $\Gamma_j \Delta t_{\text{BH}}$, is actually close to Δt_{BH} (cf. Figure 1). A very high value of the Doppler factor is required to avoid the absorption of the gamma rays due to interactions with low-energy synchrotron photons, inevitably co-produced with the gamma rays in the shock-in-jet scenario. The optical depth to pair creation by the gamma rays can be approximated by

$$\tau_{\gamma\gamma}(10 \text{ TeV}) \sim 300(\delta/4)^{-6} (\Delta t/1 \text{ min})^{-1} (L_{\text{syn}}/10^{42} \text{ erg s}^{-1}).$$

Adopting a non-thermal infrared luminosity of $\sim 1\%$ of the gamma-ray luminosity during the flare, the emission region would be transparent to the emission of 10 TeV gamma rays only if $\delta \gtrsim 10$. For the range of orientation angles inferred from radio observations, the Doppler factor is constrained to a value of $\delta < 6$ (Fig. 1). One can speculate if the inner jet, corresponding to the unresolved radio core, bends into a just-right orientation angle to produce the needed high value of the Doppler factor (see section S1.2). The probability for such an alignment seems to be rather low. Moreover, the observed radio jet does not show any signs of a perturbation of its flow direction on the parsec and kiloparsec scales. Since perturbations of the flow direction of the inner jet would later propagate to larger scales, major bends apparently never occurred in the past.

In summary, trying to interpret the data in the frame of the

shock-in-jet model meets difficulties. Considering the role of time dilation renders a solution of this problem impossible for any value of Γ_j .

Therefore, we conclude that the observations indicate a sub-horizon scale emission region of a different nature.

Possible origins of sub-horizon scale variability

Substructures smaller than the event horizon scale emitting highly anisotropic radiation (to avoid pair absorption) seem to be responsible for the minute-scale flux variations. The possible explanations fall into three categories: (i) mini-jet structures within the jets (33), (ii) jet-cloud interactions where the clouds may originate from stellar winds (34–36), and (iii) magnetospheric models (37–41), similar to those known from pulsar theory.

According to the mini-jet model (i), plasmoids resulting from magnetic reconnection traveling down the jet with a relativistic speed are responsible for the minute-scale flux variations observed in blazars. The model could help to mitigate the constraints on the bulk Lorentz factor by introducing a larger effective bulk Lorentz factor for the plasmoids. The mechanism also predicts reconnection events from regions outside of the beaming cone $\sim \Gamma_j^{-1}$ that could explain the day-scale flares from the radio galaxy M87 invoking external radiation fields as a target for inverse Compton scattering (33). However, the off-axis mini-jet luminosity depends on $(\Gamma_j \theta)^{-8}$ and the jet power required for IC 310 is two orders of magnitude higher compared to the one estimated from radio observations (see section S3.2). Thus, this model is challenged by the observed high luminosity in IC 310 during the flares.

Substructures smaller than the jet radius may also be introduced by considering interactions between clouds and the jet (ii). The original shock-in-jet model (1) considered this to be the main source of mass entrainment and predicted variability from the process. Recently, more elaborate work on the model has had some success in explaining the variability of M87 by pp-collisions due to the bombardment of clouds boiled off red giants with protons in the jet (36). However, the model is linked to the cloud crossing time of the jet and the proton-proton cooling time, both of which by far exceed the event horizon scale. Faster variability could be observed in case the cloud gets destroyed but a strong beaming effect would then be needed to explain the observed luminosities. In another variant, drift acceleration of particles along the trailing shock behind the stellar wind of a star interacting with the jet is considered. This might lead to an extremely anisotropic emission pattern. As mass-losing stars sweep across the jet, passing magnetic field lines pointing to the observer, the postulated accelerated particle beams in their trails become visible for a short time. For IC 310, the emission would have to be confined to within an angle of $\alpha \sim 10^{-5}$ rad to explain the observed variability time scale, requiring a very stable direction of the accelerated particle beams, at a large angle to the jet main thrust. Since two-fluid particle beams are prone to numerous plasma instabilities, the scenario relies on unphysical assumptions.

In magnetospheric models (iii), particle acceleration is assumed to be due to electric fields parallel to the magnetic fields. This mechanism is known to operate in the particle-starved magnetospheres of pulsars, but it could also operate in the magnetospheres anchored to the ergospheres of accreting black holes (see Fig. 5). Electric fields can exist in vacuum gaps when the density of charge carriers is too low to warrant their shortcut. The critical charge density for the vacuum gaps is the so-called Goldreich-Julian charge density. Electron-positron pairs in excess of the Goldreich-Julian charge density can be produced thermally by pho-

ton-photon collisions in a hot accretion torus or corona surrounding the black hole. It has also been suggested, that particles can be injected by the reconnection of twisted magnetic loops in the accretion flow (39). A depletion of charges from thermal pair production is expected to happen when the accretion rate becomes very low. In this late phase of their accretion history, supermassive black holes are expected to have spun up to maximal rotation. Black holes can sustain a Poynting flux jet by virtue of the Blandford-Znajek mechanism (4). Jet collimation takes place rather far away from the black hole at the scale of the light cylinder beyond $\sim 10r_g$. Gaps could be located at various angles with the jet axis corresponding to the polar and outer gaps in pulsar magnetospheres leading to fan beams at rather large angles with the jet axis. The gap emission must be highly variable, since gap height and seed particle content depend sensitively on plasma turbulence and accretion rate. For an accretion rate of $\dot{m} \sim 10^{-4}$ (in units of the Eddington accretion rate) and maximal black hole rotation, the gap height in IC 310 is expected to be $h \sim 0.2r_g$ (40) which is in line with the observations. Depending on the electron temperature and geometry of the radiatively inefficient accretion flow, its thermal cyclotron luminosity can be low enough to warrant the absence of pair creation attenuation in the spectrum of gamma rays. In this picture, the intermittent variability witnessed in IC 310 is due to a run-away effect. As particles accelerate to ultrahigh energies, electromagnetic cascades develop multiplying the number of charge carriers until their current shortcuts the gap. The excess particles are then swept away with the jet flow, until the gap reappears.

Radio galaxies and blazars with very low accretion rates allow us to obtain a glimpse of the jet formation process near supermassive black holes. The sub-horizon variability in combination with the results from direct imaging campaigns invite to explore analogies with pulsars where particle acceleration takes place in two stages. In the first stage, particle acceleration occurs in the gaps of a charge-separated magnetosphere anchored in the ergosphere of a rotating black hole, and in a second stage at shock waves in the force-free wind beyond the outer light cylinder.

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16. In special relativity the Lorentz- and Doppler factors are defined as $\Gamma_j = \frac{1}{\beta(1-\beta^2)^{1/2}}$ and $\delta = \left[\Gamma_j (1-\beta \cos \theta) \right]^{-1}$, respectively, where β denotes the dimensionless shock velocity and θ the angle between the line of sight and the direction of the jet, ignoring the cosmological $(1+z)$ factor. The apparent bolometric luminosity differs from its isotropic comoving-frame value by the factor δ^4 .
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Supplementary Materials

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Materials and Methods

Figs. S1 to S5

Tables S1 and S2

References (42–69)

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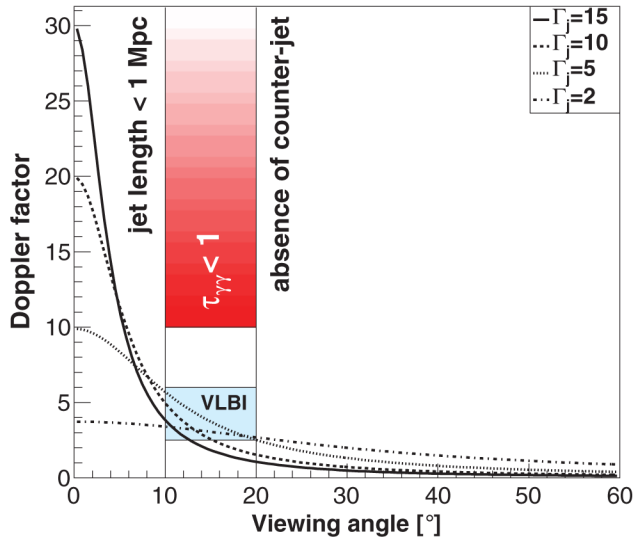
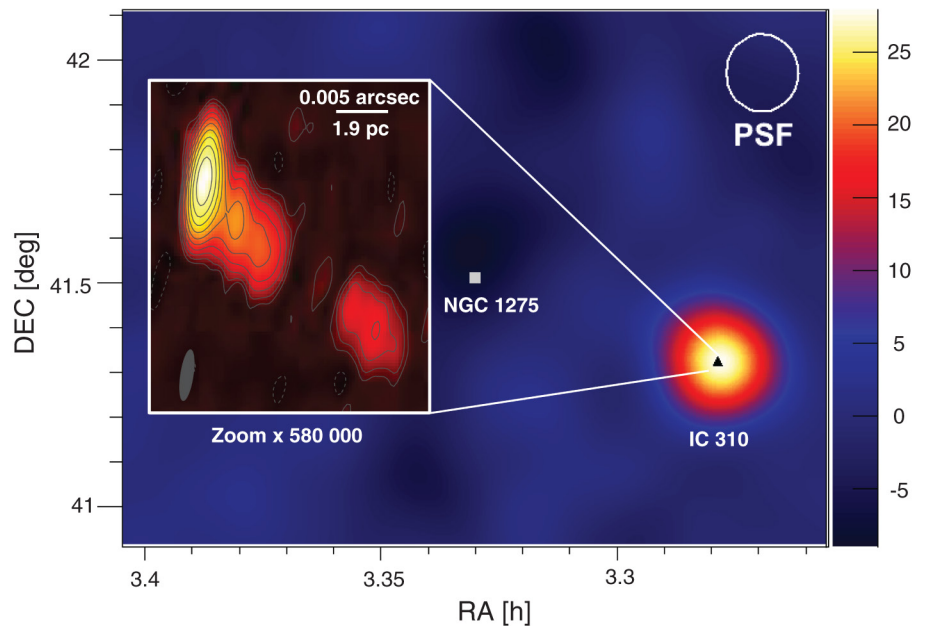


Fig. 1. The relation between Doppler factor and orientation angle evaluated for various values of the bulk Lorentz factor compared with the observational constraints of these parameters. The blue box shows the constraints on the Doppler factor arising from radio observations (32). For illustrative purposes, the red box shows the constraint from the gamma-ray optical depth to pair creation assuming $L_{\text{syn}} \sim 1\%L_{\text{VHE}}$.

Fig. 2. Significance map (color scale) of the Perseus cluster in gamma rays observed in the night of November 12/13th, 2012, with the MAGIC telescopes. The inset shows the radio jet image of IC 310 at 5.0 GHz obtained with the European VLBI Network (EVN) on October 29, 2012. Contour lines (and associated to them color scale) increase logarithmically by factors of 2 starting at three times the noise level (see supplement for image parameters). The ratio of the angular resolution between MAGIC and the EVN is 1:580 000.



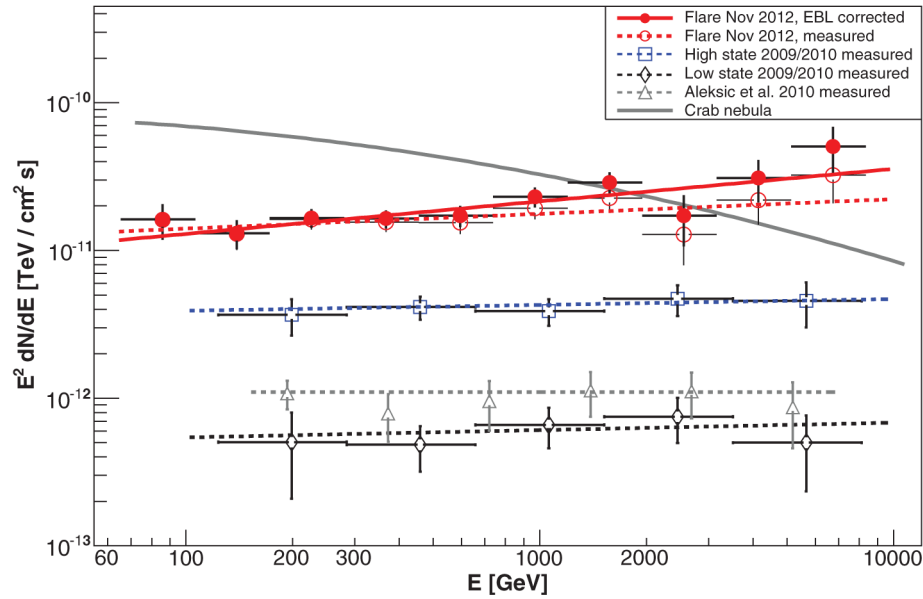


Fig. 3. Average spectral energy distributions during the flare (red) along with previous measurements of IC 310 as observed by MAGIC. We show the results from the high (blue, open squares) and low (black, open markers) states reported in (28) and the average results (gray triangles) from (27) for the whole period. The dashed lines show power-law fits to the measured spectra, and the solid line with filled circles depicts the spectrum corrected for absorption in the extragalactic background light. As a reference, the spectral power-law fit of the Crab Nebula observations from (25) is shown (gray, solid line). Vertical error bars show 1 standard deviation statistical uncertainty. Note that due to unfolding procedure spectral points are correlated. Horizontal error bars show the energy binning.

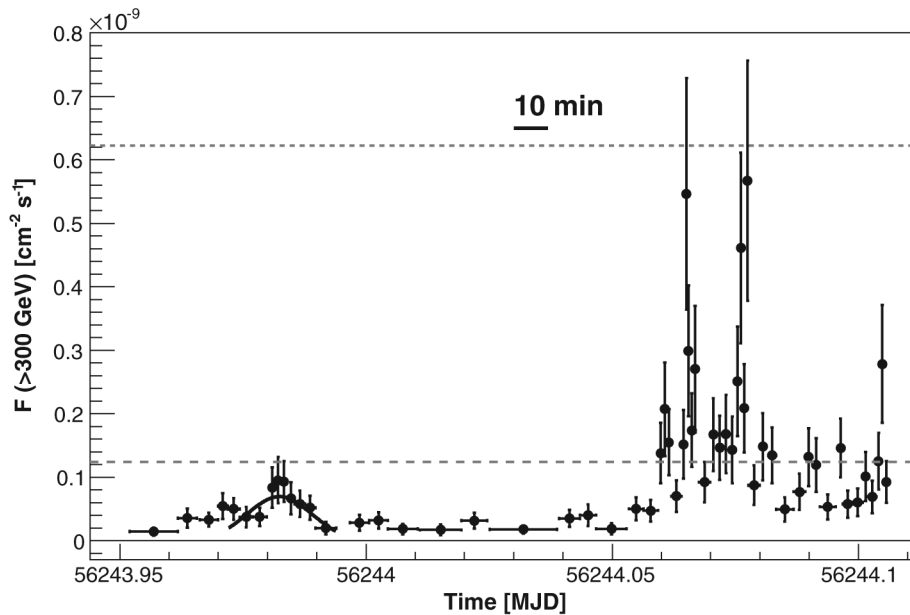


Fig. 4. Light curve of IC 310 observed with the MAGIC telescopes in the night of November 12/13th, 2012, above 300 GeV. As a flux reference, the two gray lines indicate levels of 1 and 5 times the flux level of the Crab Nebula, respectively. The precursor flare (MJD 56243.972–56243.994) has been fitted with a Gaussian distribution. Vertical error bars show 1 standard deviation statistical uncertainty. Horizontal error bars show the bin widths.

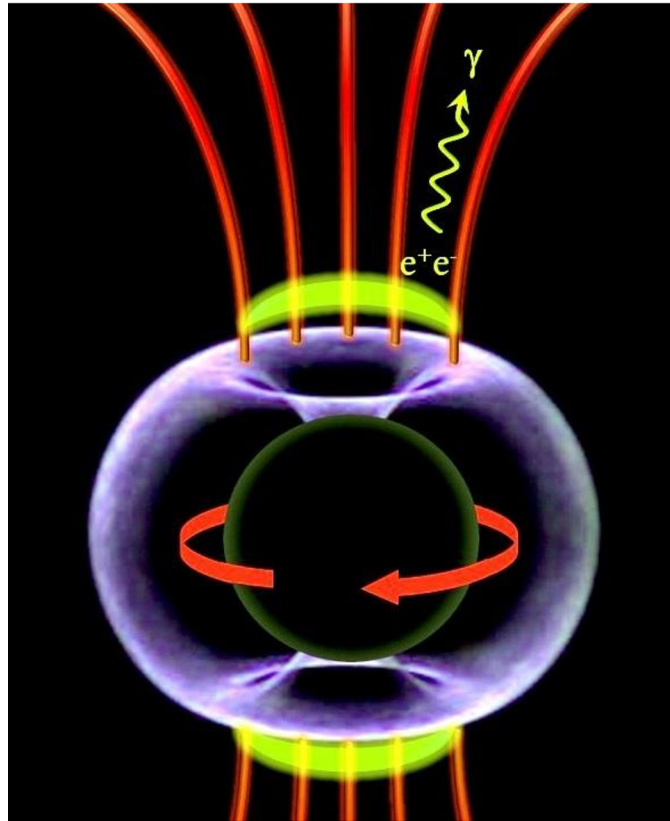


Fig. 5. Scenario for the magnetospheric origin of the gamma-rays: A maximally rotating black hole with event horizon r_g (black sphere) accretes plasma from the center of the galaxy IC 310. In the apple-shaped ergosphere (blue) extending to $2r_g$ in the equatorial plane, Poynting flux is generated by the frame-dragging effect. The rotation of the black hole induces a charge-separated magnetosphere (red) with polar vacuum gap regions (yellow). In the gaps, the electric field of the magnetosphere has a component parallel to the magnetic field accelerating particles to ultra-relativistic energies. Inverse-Compton scattering and copious pair production due to interactions with low-energy thermal photons from the plasma accreted by the black hole leads to the observed gamma rays.